Development of an Accurate Tool for Path Loss and Coverage Prediction in Indoor Environments

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***Abstract*—A tool has been developed to predict path loss in indoor environments. The concept of the tool is discussed and its performance is compared with the performance of a ray-tracing tool. The tool is validated with measurements on another floor in the same building and measurements in another building.**

I. Introduction

The characterization of path loss in indoor environments has been the subject of extensive research and many models have been proposed to make accurate predictions. Statistical models are easy to obtain when a lot of measurement data is available, but their validity is limited to the category of buildings they represent. Ray-tracing tools therefore take into account the geometry of the building and the used materials. However, the results appear to be very dependent on geometrical details of the ground plan, which force the user to work with very accurate plans. Also, the number of allowed interactions (transmissions, reflections, and diffractions) have a huge influence on the predicted path loss: differences up to 5 dB have been observed for the average path loss along a line-of-sight (LoS) path when this number of allowed interactions is adapted (see Section VI-A). Finally, for a high number of interactions, calculation time of ray-tracing tools may run to a range of days.

In this paper, a tool to predict wireless reception quality and path loss is proposed. The tool avoids the problems of both methods mentioned above. This method is implemented in a web service prediction tool with a Java engine that allows the user to draw or import a ground plan of a building and predict the path loss at 2.4 GHz in the different rooms on a floor level. Measurements have been performed in two buildings in Ghent, Belgium for modelling and validating the tool. A comparison with ray-tracing simulations is executed. In the next sections the concept of the tool is explained, the measurement setup is discussed, and different aspects of the prediction tool are explained. Then, the tool parameters are modeled and the tool prediction is validated.

II. Concept

An accurate heuristic tool has been developed for the prediction of wireless coverage (see Section IV) in zones of about 5 m^2. The dominant path is determined with a multi-dimensional optimisation algorithm that searches the lowest total path loss, consisting of a distance loss, a cumulated wall loss, and an interaction loss. Measurements on one floor of an office building have been performed to investigate propagation characteristics. The wall penetration losses have been determined and interaction loss have been fitted to match these measurements. Measurements on another floor of the same building and in another building have been executed to validate the tool with only limited additional tuning (the interaction loss depends on the dominant wall material in the environment). This and the fact that the free-space loss model is used for every environment make the tool generally applicable, while other tools are often too dependent of the environment upon which the used propagation model is based. Finally, our tool is offered to both professional and non-professional users through a web service, which means that no software has to be installed, the presence of internet connection is sufficient.

III. Measurement setup

Path loss measurements have been performed in two buildings in Ghent, Belgium. The transmitter Tx is an omnidirectional antenna (gain = 4.5 dBi) at a height of 2.5 m (typical height of access point in office environments) and at a frequency of 2.4 GHz (WLAN frequency band). The signal is a continuous sine wave and the Equivalent Isotropically Radiated Power (EIRP) is 20.39 dBm. The receiver antenna (identical to Tx) is attached to a cart at a height of 1 m (typical laptop height) and is connected to a spectrum analyser. The spectrum analyser is connected to a laptop used to record and process the measurement data. The measurements are executed while the cart is moved along straight trajectories.

IV. Prediction tool

In this section the ground plan format is discussed and the prediction algorithm is presented. Our goal is to develop an accurate, but fast tool that does not make use of extensive fitting to obtain good predictions, as this often leads to results, which are only usable for the investigated building.

A. *Floor plan*

The tool is constructed as a web service which allows to import an existing floor plan in different formats or to draw a floor plan of a building, where the user can choose between different wall materials. The web service transfers this floor plan to a Java backend, after which the server responds with predicted throughput and pathloss, which the drawing tool turns into a colour-coded visualisation superimposed over the floor plan. This gives the user a clear view on the estimated wireless connection quality (coverage) in each area, as shown in Fig. 1. The user interface of the application was developed using an iterative design process in close collaboration with usability experts (CUO, Centre for User Experience Research).

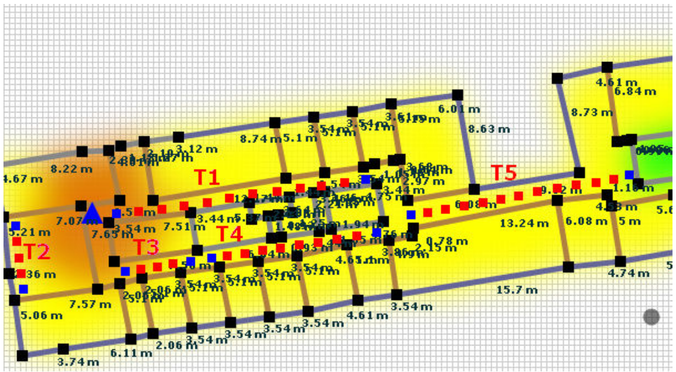

Fig. 1. Measurement trajectories on the second floor, drawn on floor plan with indication of access point (blue triangle) and predicted path loss with color code (orange: PL<60 dB, yellow: 60 dB<PL<80 dB, green: PL>80 dB).

B. Prediction algorithm.

The planning tool will predict the indoor coverage by means of path loss (PL) prediction based on the Indoor Dominant Path Model (IDP) [1]. This model is a compromise between empirical models only considering the ”direct” ray between transmitter Tx and receiver Rx (e.g., multi wall model) and ray-tracing models where hundreds of rays and their interactions with the environment are investigated. In the IDP model, propagation focuses on the dominant path between transmitter and receiver, i.e. the path along which the signal encounters the lowest obstruction in terms of path loss. It takes into account the path length along the path, the number and type of interactions (e.g., reflection, transmission, etc.), the material properties of the objects encountered along the path, etc. The approach of using the IDP model is justified by the fact that more than 95% of the energy received is contained in only 2 or 3 rays [1]. According to [1], predictions made by IDP models reach the accuracy of ray-tracing models or even exceed it. Different propagation properties can be chosen to be included into the IDP model, with a trade-off between complexity and accuracy. We have chosen to take into account the distance along the dominant path (distance loss), the corresponding wall losses, and the propagation direction changes along the dominant path (interaction loss). The algorithm for calculating this path loss using this model will be discussed hereafter.

C. Implementation

The receiver locations where the path loss is calculated are the points of a grid, for which the grid size can be set as a parameter by the user. First of all, we need to define the meaning of ’a path’: this is a possible sequence of walls a ray can propagate through to reach room B from room A. When room A is the same as room B, a possible path is the empty path: no walls have to be crossed to get from A to B. Mostly, different paths are possible for a given couple of rooms, and this number of possible paths generally increases exponentially as the number of rooms on the floor increases. The total path loss for each of the paths is the sum of the total wall loss along this path, the distance loss along this path (calculated using a one-slope model), and the interaction loss along this path (both discussed further). The total path loss of a certain path can thus be calculated as follows:

$$\mathrm{PL} = \mathrm{PL_0} + 10\ \mathrm{n}\ \log(\frac{\mathrm{d}}{\mathrm{d_0}}) + \sum_{\mathrm{i}} \mathrm{L_{W,i}} + \sum_{\mathrm{i}} \mathrm{L_{B,i}}, \quad (1)$$

where PL [dB] is the total path loss along the path, $\mathrm{PL_0}$ [dB] is the path loss at a distance of $\mathrm{d_0}$, d [m] is the distance along the path between access point and receiver (obtained as explained in the algorithm), $\mathrm{d_0}$ [m] is a reference distance, and n [-] is the path-loss exponent. $\mathrm{d_0}$ was chosen 1 m here. The first two terms of the sum represent the path loss coming from the distance along the considered path; this will be noted here as the ”distance loss”. For this distance loss model, the free-space model is used ($\mathrm{PL_0} = 40.00$ dB and n = 2) as this model involves no fitting and no tuning of the tool to agree with existing measurement data. $\sum_{\mathrm{i}} \mathrm{L_{W,i}}$ is the cumulated wall loss along this path (i.e., the sum of the wall losses $\mathrm{L_{W,i}}$ of the walls $\mathrm{W,i}$ along the path, i = 1,. . .,w, where w is the total number of walls along the path). The penetration losses of the walls are based on available literature and on measurements. $\sum_{\mathrm{i}} \mathrm{L_{B,i}}$ is the cumultated loss $\mathrm{L_{B,i}}$ caused by the bend $\mathrm{B,i}$ of the propagation path from access point to receiver. It is based on measurements executed in the investigated buildings.
To find the path that is dominant, we have to find the path for which the sum of the distance loss, the wall loss, and the interaction loss is minimal. We assume thus that this path represents almost the total energy. The minimisation will be performed by a multi-dimensional optimization algorithm.

1) Algorithm: In this section, the algorithm used for determining the dominant path is discussed. The **dominant path** is defined as the path for which the sum of the cumulated wall loss, the distance loss, and the interaction loss is the lowest.

The path loss between a certain grid point and a certain access point is determined by calculating the path loss for all possible paths between access point and grid point, where optimizations are implemented in order to speed up the calculations. Fig. 2 shows an example groundplan of a floor level, where the paths from a random grid point in room 3 (marked with a black dot) to the access point (in room 4) are determined. A tree is created with as root the room in which the investigated grid point is located (e.g., room 3 of Figs. 2 and 3). Each branch corresponds to a wall connecting two rooms with as weight the wall loss between both rooms. For each new room in the tree, new branches are originated.

Fig. 3 shows the tree corresponding with the groundplan of Fig. 2 for the proposed algorithm. In both figures, the rooms are indicated with numbers in squares, and the walls with letters in circles. For reasons of clarity, exterior walls are not included in the tree in Fig. 3, since they always lead to the termination of a certain branch. In order to find a path as quickly as possible, the branches are added so that the walls closest to the access point are added first. Because the tree is built in a "depth-first" way, the algorithm leads to a solution as fast as possible. This process of originating new branches will eventually be stopped, as a result of one of the following four occurrences:

1) The room of the access point is reached: the path will be added to the list of possible paths from transmitter to receiver
2) An exterior wall is crossed: this branch is terminated
3) A wall is crossed that is already present in the path: this branch is terminated
4) The room with the access point cannot be reached from the current room with a path loss that is lower than the path loss that is currently the lowest.

Each time the room with the access point is reached, the total loss is calculated (cumulated wall loss + distance loss + interaction loss). If the total loss for this new path is lower than the current lowest loss, the best path is updated. The distance loss for a certain path is calculated as the free-space loss of the length of the path that traverses all the walls of the considered path. The interaction loss is the sum of all the losses caused by each single propagation direction change of the path. The relation between the loss and the angle of the direction change is determined from path loss measurements in two perpendicular corridors.

The second and third reason for stopping to originate new branches can be observed in the figure: branches are terminated when a wall is crossed that is already present in the path or when the room of the access point (i.e., room 4) is reached. For the ground plan of Fig. 2, the tree in Fig. 3 yields the following paths, consisting of a sequence of walls to go from room 3 to room 4: B-A-F, B-E, B-D-G, C-G, C-D-A-F, C-D-E. In this example, the branching has not been interrupted because of the fourth reason.

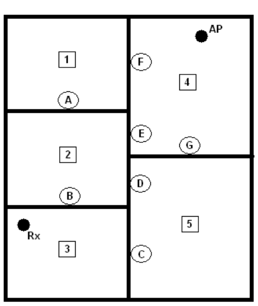

Fig. 2. Example of ground plan (rooms 1-5, walls A-G, AP = access point, Rx = receiver).

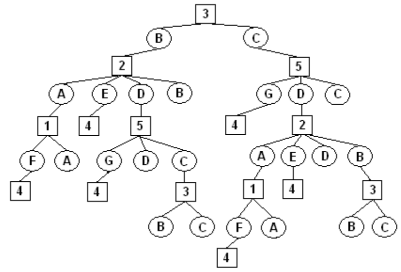

Fig. 3. Tree yielding all possible paths from room 3 to room 4.

V. Modeling the parameters of the dominant path model

In this section the model parameters will be determined, based on measurement performed on the **second floor** of the Zuiderpoort building, a typical office building. Since the distance loss will be calculated with the free-space loss model, the values for PL_0, d_0, and n are chosen equal to 40.00 dB, 1 m, and 2, respectively.

A. Wall loss $\sum_{\mathrm{i}} \mathrm{L}_{\mathrm{W,i}}$

To determine the path loss increase when a certain wall is penetrated along a given path, we have based ourselves on available literature, except for the layered drywalls (orange walls in Fig. 4), of which we measured the penetration loss ourselves (2 dB). For concrete, a value of 10 dB was used, and for glass (windows or glass doors) 2 dB.

B. Interaction loss $\sum_{\mathrm{i}} \mathrm{L}_{\mathrm{B,i}}$

Measurements on the second floor of the Zuiderpoort building allowed us to determine the relation between the angle made by a propagation path and the additional loss associated with the propagation direction change. Because the interaction loss should be the same for e.g., three changes of 30° and one change of 90°, a linear relationship is proposed.

$$\mathrm{L}_{\mathrm{B,i}} \;=\; \mathrm{A} \cdot \hat{\mathrm{B}}_{\mathrm{i}} \tag{2}$$

where $\mathrm{L}_{\mathrm{B,i}}$ [dB] is the loss caused by bend B_{i}, A [dB/°] is a parameter depending on the dominant material in the building and $\hat{\mathrm{B}}_{\mathrm{i}}$ is the angle corresponding with bend B_{i} [°]. Based on measurements in two perpendicular corridors, A was determined at 0.0556 dB/° (mainly layered drywalls) and 0.1946 dB/° (mainly concrete walls) for the Zuiderpoort and the De Vijvers buildings respectively.

C. Results for second floor of Zuiderpoort building

The model of eq. (1) with the model parameters chosen as explained above is now used to calculate the deviations between the tool predictions and the measurements for the second floor of the Zuiderpoort building. Fig. 1 shows the ground plan of (a part of) the second floor as it is shown as output by the webservice of our own tool. The color code is explained in the figure caption. In Fig. 1 we have drawn the measurement trajectories with the indication of the access point (blue triangle) and the predicted path loss.

Table I shows for all trajectories on the second floor (used for modeling) and third floor (used for validation) the measured average path loss $\mathrm{PL}_{\mathrm{ms}}$ [dB], the predicted path loss $\mathrm{PL}_{\mathrm{pr}}$ and deviation δ [dB] = $\mathrm{PL}_{\mathrm{pr}}$ - $\mathrm{PL}_{\mathrm{ms}}$ for the considered model for Tx and Rx at heights of 2.5 m and 1 m respectively. Low deviations are obtained. An average for the absolute value of the deviation $|\delta|$ is 1.96 dB for the second floor.

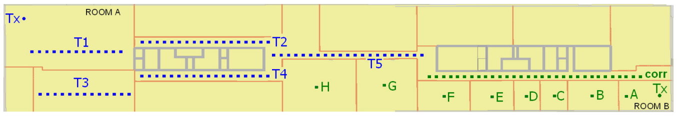

Fig. 4. Measurement trajectories on the third floor.

	$\mathrm{PL}_{\mathrm{ms}}$ [dB]	$\mathrm{PL}_{\mathrm{pr}}$ [dB]	δ [dB]		$\mathrm{PL}_{\mathrm{ms}}$ [dB]	$\mathrm{PL}_{\mathrm{pr}}$ [dB]	δ [dB]
T1(2)	56.9	61.1	-4.2	**F**	79.6	79.0	0.6
T2(2)	58.7	59.9	-1.2	**G**	82.3	78.6	3.7
T3(2)	63.7	61.3	2.4	**H**	84.9	81.8	3.1
T4(2)	69.6	67.7	1.9	**corr**	66.9	66.9	0.0
T5(2)	79.2	79.3	-0.1	**T1(3)**	58.1	59.1	-1.0
A	50.3	53.3	-3.0	**T2(3)**	70.1	70.4	-0.3
B	61.7	61.4	0.3	**T3(3)**	65.5	65.2	0.3
C	64.1	67.4	-3.3	**T4(3)**	78.9	73.5	5.4
D	65.9	71.3	-5.4	**T5(3)**	79.7	78.4	1.3
E	68.6	75.4	-6.8				

TABLE I
MEASURED AVERAGE PATH LOSS $\mathrm{PL}_{\mathrm{ms}}$ [DB] ALONG DIFFERENT TRAJECTORIES, PREDICTED AVERAGE PATH LOSS $\mathrm{PL}_{\mathrm{pr}}$ [DB] AND THEIR DEVIATIONS δ [DB] FROM $\mathrm{PL}_{\mathrm{ms}}$. (BUILDING FLOOR IS INDICATED BETWEEN BRACKETS FOR TRAJECTORIES WITH THE SAME NAME.)

VI. VALIDATION OF TOOL PREDICTION

The parameter values of our prediction tool are based on measurements on 1 floor of 1 building (second floor, Zuiderpoort, see Section V). In this section, we validate the general applicability of our tool by firstly comparing with ray-tracing simulations and secondly by comparing with measurements on another floor and in other buildings.

A. Results for ray-tracing tool REMCOM

In this section, some of the trajectories are simulated with the commercial ray-tracing tool REMCOM. The simulation results for twelve measurements are analysed and compared with the measurements. The path loss for these cases is predicted by REMCOM simulations. Four different simulation configurations are investigated and compared, where the number of allowed reflections, transmissions, and diffractions are varied. The following four simulation settings are investigated: 6 reflections, 8 transmissions, and 1 diffraction allowed (6R 8T 1D), 4 reflections, 6 transmissions, and 1 diffraction allowed (4R 6T 1D), 2 reflections, 2 transmissions, and 1 diffraction allowed (2R 2T 1D), and 1 reflections, 4 transmissions, and 1 diffraction allowed (1R 4T 1D).

Table II shows the measured average path loss $\mathrm{PL}_{\mathrm{meas}}$ [dB] along *trajectories T1, T2, and T4* (see Fig. 4), as well as the simulated average path loss $\mathrm{PL}_{\mathrm{sim}}^{\mathrm{ray}}$ [dB] (raytracing) along the trajectories for the four simulation settings and their deviations δ [dB] from $\mathrm{PL}_{\mathrm{meas}}$. It shows that there are large differences between the four ray-tracing simulation settings. For the relatively 'easy' trajectories T1 (LoS trajectory) and T2 (adjacent room), differences up to 5.0 dB (47.9 dB vs. 52.9 dB) and 8.3 dB (50.8 dB vs. 59.1 dB) are obtained.

Table II also compares the measured average path loss $\mathrm{PL}_{\mathrm{meas}}$ [dB] along a trajectory in the *corridor* (corr) and in *rooms A-H* (see Fig. 4), as well as the predicted average path loss $\mathrm{PL}_{\mathrm{sim}}^{\mathrm{ray}}$ [dB] for the four simulation settings and their deviations δ [dB] from $\mathrm{PL}_{\mathrm{meas}}$. It shows again that there are very large differences between the four ray-tracing simulation settings. Close to the transmitter (A, B, C, corr), 1R 4T 1D is the best choice. It should be noted that for 2R 2T 1D and 1R 4T 1D, not all trajectories could be calculated (see '-' in Table II). For 6R 8T 1D the calculation time is over one day.

We can conclude that the path loss predicted by REMCOM depends heavily on the simulation settings, that the optimal simulation setting depends on the investigated location, and that the calculation time is very high when more reflections, transmissions, and diffractions are allowed.

	$\mathrm{PL}_{\mathrm{meas}}$ **[dB]**	**6R 8T 1D** $\mathrm{PL}_{\mathrm{sim}}^{\mathrm{ray}}$ **[dB]**	**4R 6T 1D** $\mathrm{PL}_{\mathrm{sim}}^{\mathrm{ray}}$ **[dB]**	**2R 2T 1D** $\mathrm{PL}_{\mathrm{sim}}^{\mathrm{ray}}$ **[dB]**	**1R 4T 1D** $\mathrm{PL}_{\mathrm{sim}}^{\mathrm{ray}}$ **[dB]**
T1	58.1	47.9 (10.2)	48.3 (9.8)	50.5 (7.6)	52.9 (5.2)
T2	70.1	50.8 (19.3)	51.2 (18.9)	55.4 (14.7)	59.1 (11)
T4	78.9	57.9 (21.0)	59.2 (19.7)	86.3 (-7.4)	73.1 (5.8)
A	50.3	45.5 (4.8)	45.4 (4.9)	46.9 (3.4)	49.3 (1)
B	61.7	50.9 (10.8)	49.1 (12.6)	51.9 (9.8)	55.4 (6.3)
C	64.1	52.2 (11.9)	50 (14.1)	56.2 (7.9)	57.8 (6.3)
D	65.9	54.6 (11.3)	52.7 (13.2)	97.5 (-31.6)	61.3 (4.6)
E	68.6	56.7 (11.9)	55.6 (13)	-	67.1 (1.5)
F	79.6	59 (20.6)	59.2 (20.4)	-	-
G	82.3	63.5 (18.8)	68.9 (13.4)	-	-
H	84.9	69.4 (15.5)	78.4 (6.5)	-	-
corr	66.9	51.9 (15)	51.1 (15.8)	59.1 (7.8)	58.9 (8)

TABLE II
MEASURED AVERAGE PATH LOSS $\mathrm{PL}_{\mathrm{meas}}$ [DB] ALONG DIFFERENT TRAJECTORIES, PREDICTED AVERAGE PATH LOSS $\mathrm{PL}_{\mathrm{sim}}^{\mathrm{ray}}$ [DB] FOR THE FOUR SIMULATION SETTINGS AND (BETWEEN BRACKETS) THEIR DEVIATIONS δ [DB] FROM $\mathrm{PL}_{\mathrm{meas}}$ (TRANSMITTER HEIGHT = 2.5 M, RECEIVER HEIGHT = 1 M.

B. Validation of the tool prediction with measurements in other buildings

1) Validation with measurements on third floor of Zuiderpoort building: Fig. 4 shows the third floor of the Zuiderpoort building. These presented measurement trajectories serve as a first validation for the model proposed in Section V (based on measurements on second floor of Zuiderpoort building).

Table I shows for all trajectories on the third floor (T1-T5, A-H, and corr) the measured average path loss $\mathrm{PL}_{\mathrm{ms}}$ [dB], the predicted path loss $\mathrm{PL}_{\mathrm{pr}}$ and deviation δ [dB] = $\mathrm{PL}_{\mathrm{pr}}$ - $\mathrm{PL}_{\mathrm{ms}}$ for the considered model for Tx and Rx at heights of 2.5 m and 1 m respectively. The measurements on the third floor served as a validation for the model that was created based on measurements on the second floor. An average absolute value for the deviations on the third floor is only 2.46 dB. Compared to literature, this is a low deviation. In [1], the obtained deviations are similar, but δ was considered there to calculate average deviations, while we considered $|\delta|$. This section shows that the obtained model for the tool is valid for a similar propagation environment (same building materials used) without tuning of the parameters in contrary to e.g., [2]. If we thus compare the agreement of $\mathrm{PL}_{\mathrm{pr}}$ (Table I) and $\mathrm{PL}_{\mathrm{sim}}^{\mathrm{ray}}$ (Table II) with the measurements $\mathrm{PL}_{\mathrm{meas}}$, it is clear that the best agreement is obtained for our tool and no dependency of tool settings is present.

2) Validation with measurements in 'De Vijvers': A measurement campaign on the ground floor in 'De Vijvers', a retirement home, has been considered as a second validation case. Path loss measurements $\mathrm{PL}_{\mathrm{meas}}$ have been performed for twelve measurement trajectories and the results are compared with the tool prediction $\mathrm{PL}_{\mathrm{pred}}$, which is only based on measurements on the second floor of the Zuiderpoort building (see Section V). Fig. 5 shows the ground plan of 'De Vijvers'. For trajectory T1 (purple rectangle) the purple transmitter (purple dot) was active, for trajectories T2-T12 (blue rectangles) the blue transmitter (blue dot). Table III shows the measured path loss for trajectories T1-T12, the path loss predicted by the tool, and the deviation between measurement and prediction. It shows that the predictions match the measurements excellently, the maximum deviation is 5.07 dB for T9. The deviations are low especially for the trajectories with the lowest path losses (T1, T2, T11, T12) which will be most relevant for actual networks (locations on trajectories with PL > 90 dB will probably have no WiFi reception). The average deviation for T1-T12 is only 1.74 dB (standard deviation = 1.76 dB). From these low deviations we can conclude that the model is also valid for a different environment than the one for which the model was originally constructed. Only the interaction loss model (see eq.(2)) has been adapted, based on two perpendicular measurement trajectories (T2 and T3 in Fig. 5).

VII. Conclusions

A tool has been developed to predict path loss in indoor environments. The concept of the tool is explained and its performance is validated with measurements in other buildings. In contrary to a lot of existing tools no tuning of the tool's parameters is performed for the validation. Excellent correspondence between measurements and predictions is obtained, even for other buildings and floors, demonstrating the general applicability of the proposed approach. Finally, measurements and the tool's predictions are compared with ray-tracing simulations. Ray-tracing tools appear to be very dependent on the simulation settings for path loss predictions

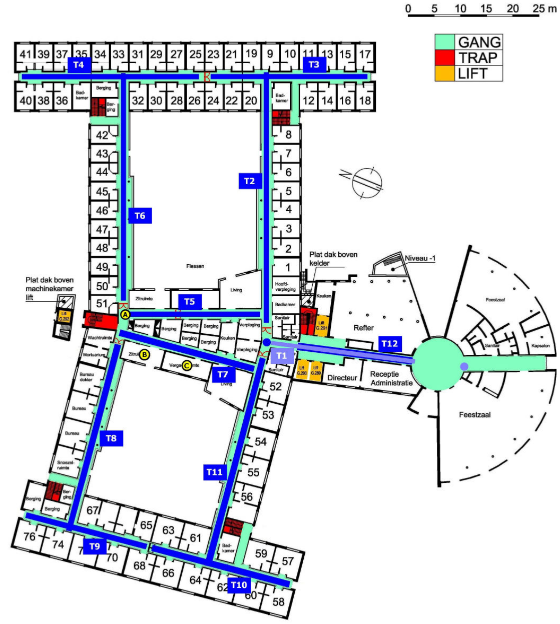

Fig. 5. Ground plan of 'De Vijvers' with indication of transmitters (blue and purple dots), measurement trajectories (blue and purple rectangles).

	$\mathrm{PL}_{\mathrm{meas}}$ **[dB]**	$\mathrm{PL}_{\mathrm{pred}}$ **[dB]**	δ **[dB]**		$\mathrm{PL}_{\mathrm{meas}}$ **[dB]**	$\mathrm{PL}_{\mathrm{pred}}$ **[dB]**	δ **[dB]**
T1	66.56	66.74	-0.18	**T7**	84.45	82.01	2.44
T2	68.78	68.82	-0.04	**T8**	97.59	99.67	-2.08
T3	91.28	92.00	-0.72	**T9**	100.56	95.49	5.07
T4	96.88	96.96	-0.08	**T10**	96.20	91.71	4.49
T5	83.42	83.39	0.03	**T11**	70.36	67.83	2.53
T6	99.30	96.67	2.63	**T12**	64.36	63.75	0.61
				T1-T12			**1.74**

TABLE III
Measured path loss $\mathrm{PL}_{\mathrm{meas}}$, predicted path loss $\mathrm{PL}_{\mathrm{pred}}$ for trajectories T1-T12 and for locations A-C, and deviations between measurement and prediction.

in indoor environments and are thus less suitable for general application.

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